Applied Neuroscience

Columbia Science Honors Program

Spring 2017

Prediction, Cognition, and the Brain

Test Your Intuition

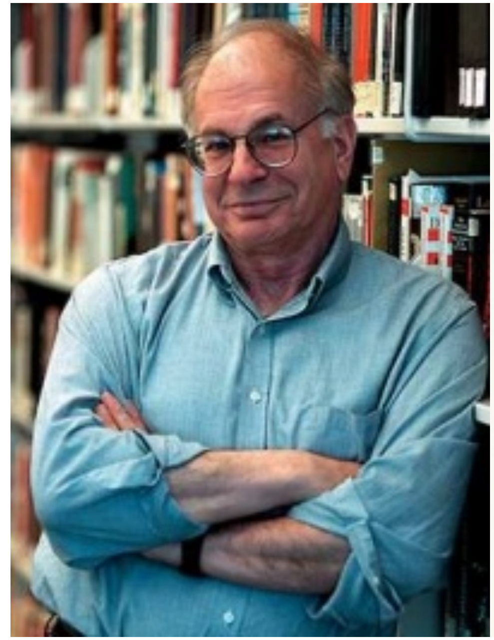
A bat and ball cost $1.10.
The bat costs one dollar more than the ball.
How much does the ball cost?

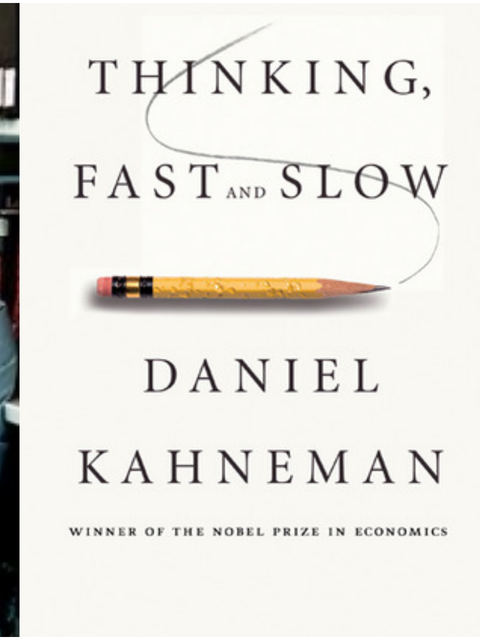
Human Intuition

<u>*Explanation:*</u>
Our intuition tells us the ball costs $0.10— However, that implies the bat costs $1.10 for a sum of $1.20. The correct answer is $0.05.

Daniel Kahneman and Amos Tversky believe that we:

- lack statistical intuition
- judgments and decisions deviate in identifiable ways from idealized economic models
- **errors are not only common but also predictable**





Prediction

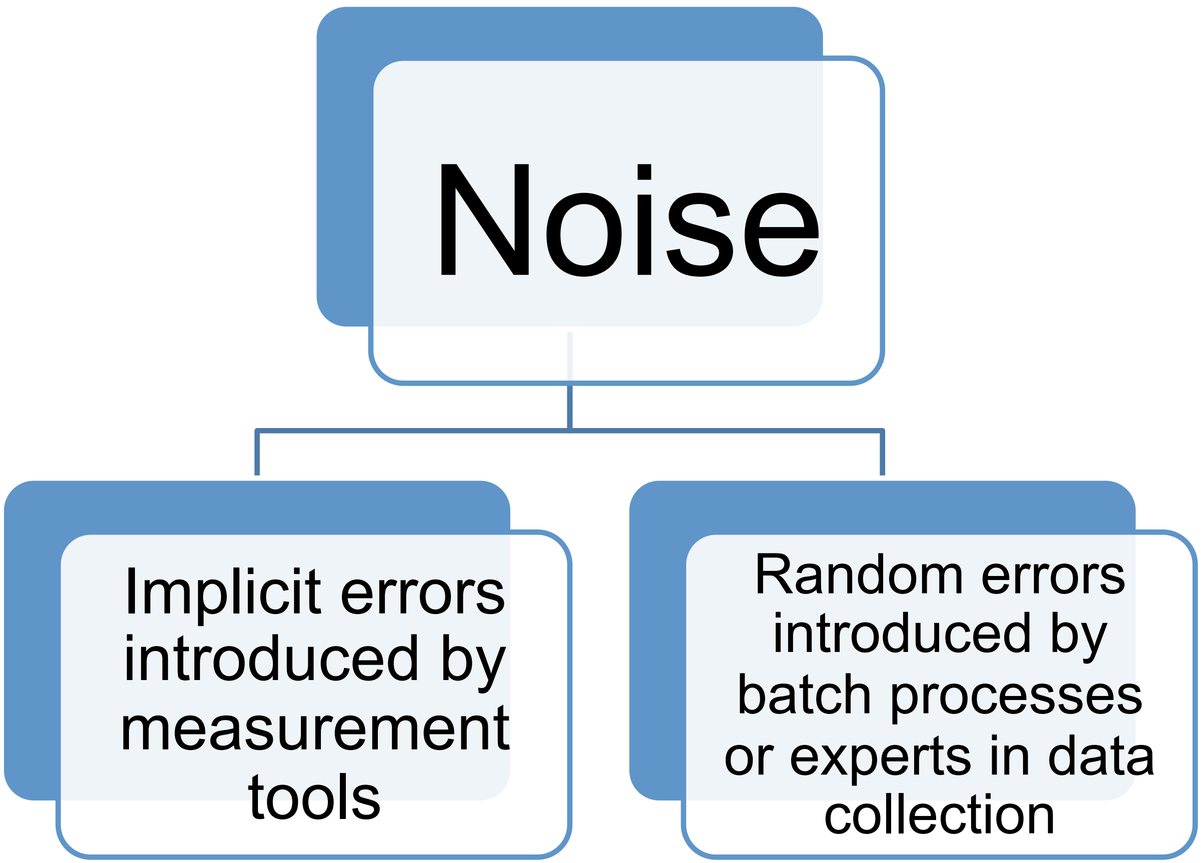
Objective: Role of Predictive Models

Agenda:

1. Noise in the Brain
2. Guest Lecture
   Professor Joshua Jacobs
3. Computer Intuition
   Predictive Models

Prediction and Its Limits

A major challenge for using data to make predictions is distinguishing what is meaningful from noise.



To mitigate the effects produced by noise:

1. Adaptation of the algorithms to properly handle the noise
2. Pre-processing of the datasets aiming to remove or correct the noise

Noise in the Nervous System

Noise: random or unpredictable fluctuations and disturbances that are not part of a signal.

Spike: an action potential interpreted as a unitary pulse signal (that is, it either is or is not present), the timing of which determines its information content. Other properties of the action potential, such as its shape or depolarization levels, are ignored.

Variability is a feature of behavior that is also present at the neuronal level.

In this case, variability is defined as changes in a measurable quality (i.e. spike timing)

Noise contributes to variability at the cellular and behavioral level. This is especially important in:

- Perception
- Decision-Making
- Motor Behavior

Sources of Noise in the Brain

- **Thermal noise**
- **Cellular noise**
  - ❖ *Stochastic opening and closing of ion channels*
  - ❖ *Membrane voltage fluctuations in the axons and dendrites*
- **Synaptic noise**
- **Sensory noise**
  - ❖ *Random generation of voltage fluctuations in fibers*
- **Motor noise**
- **Environmental (Stimulus) noise**

Sensory Noise

Trial-to-Trial Variability: the differences between responses that are observed when the same experiment is repeated in the same specimen (for example, in the same neuron or in the same subject).

Poisson Process: A random process that generates binary (yes or no) events for which the probability at any small interval is low.

External sensory stimuli are intrinsically noisy:

- Chemical senses
  - Olfaction (smell)
  - Gustation (taste)

  Molecules can arrive at receptors at random rates owing to diffusion ***and*** *receptor proteins are limited in their ability to accurately count the number of signaling molecules.*

- Visual sense

  Vision involves absorption of photons at a rate governed by the Poisson process.

Poisson Distribution

Suppose you typically get 4 pieces of mail per day. That becomes your expectation, but there will be certain a spread:

- Sometimes a little more
- Sometimes a little less
- Once in while nothing at all

The Poisson distribution will tell you how likely it is you will get 3, or 5, or 11, or any other number of pieces of mail, during one period of observation.

It predicts the degree of spread around a known average rate of occurrence.

The formula for a Poisson distribution is

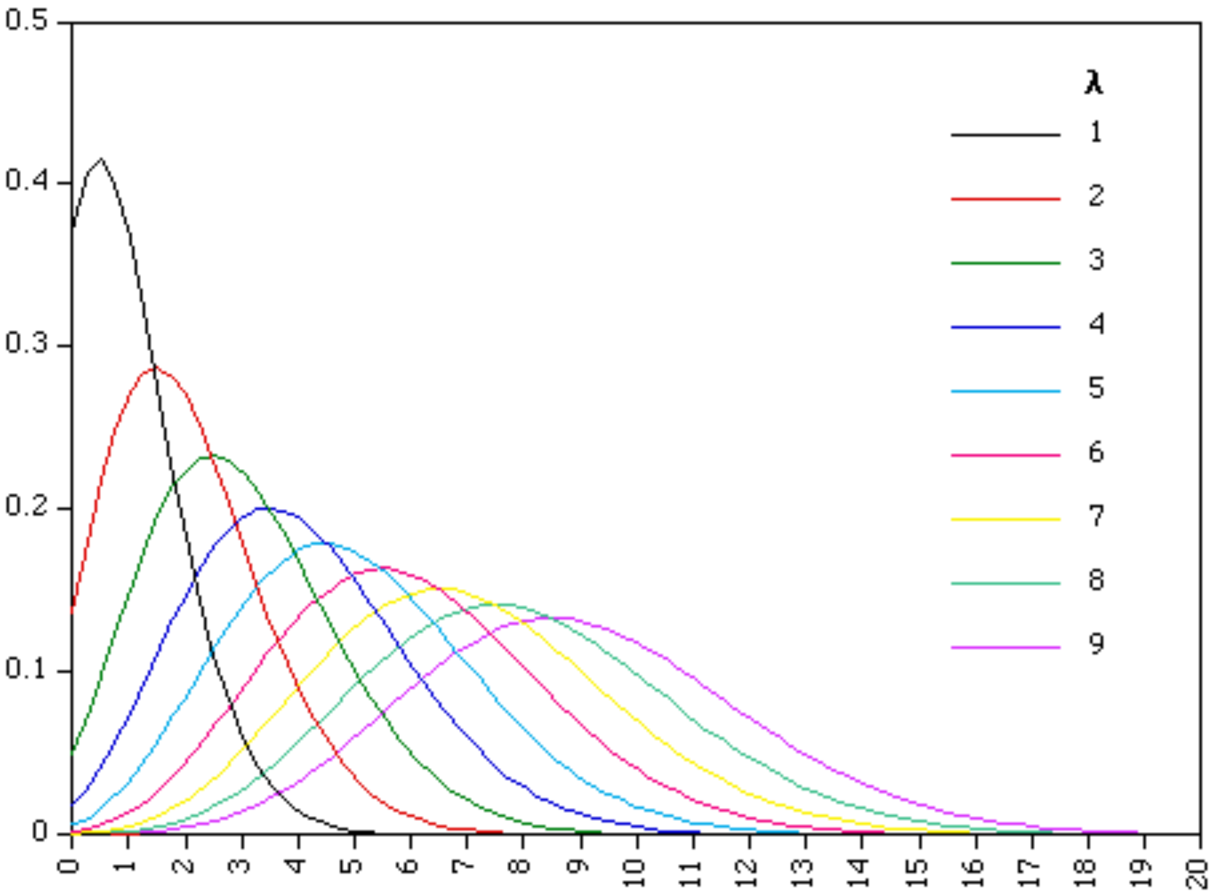
$$P(X = a) = \frac{e^{-\lambda}\lambda^{a}}{a!}$$

Where λ = average number of events

a = number of successes

The mean is λ

Poisson Distribution



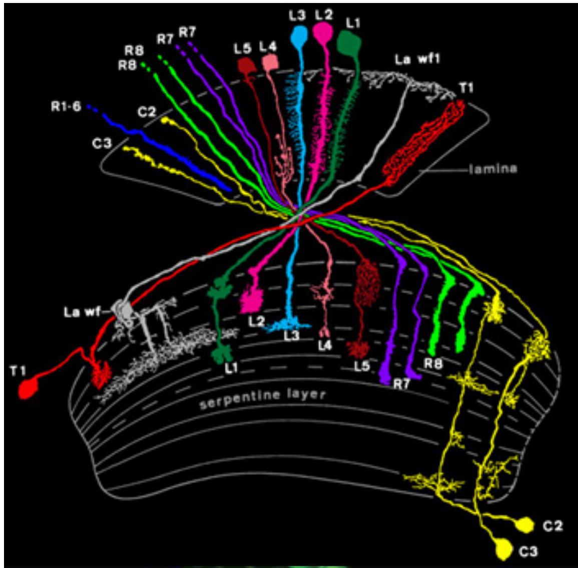
The Poisson distribution applies when:

1. Event can be counted in whole numbers.
2. Occurrences are independent.
3. Average frequency of occurrence for time period in question is known.

Sensory Noise

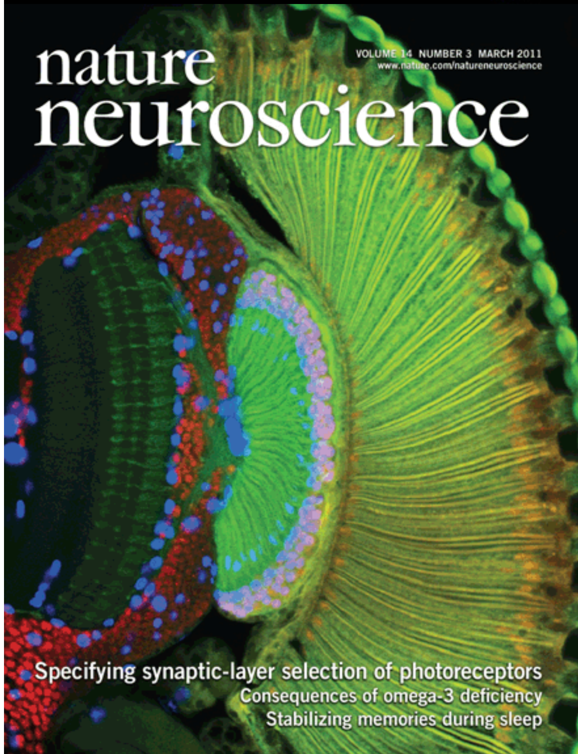
Data Processing Inequality Theorem:

- Information content of a signal cannot be increased by a local physical operation
- In sensory systems, this means that later stages of information processing (even if noise-free) cannot extract more information than is present at earlier stages.

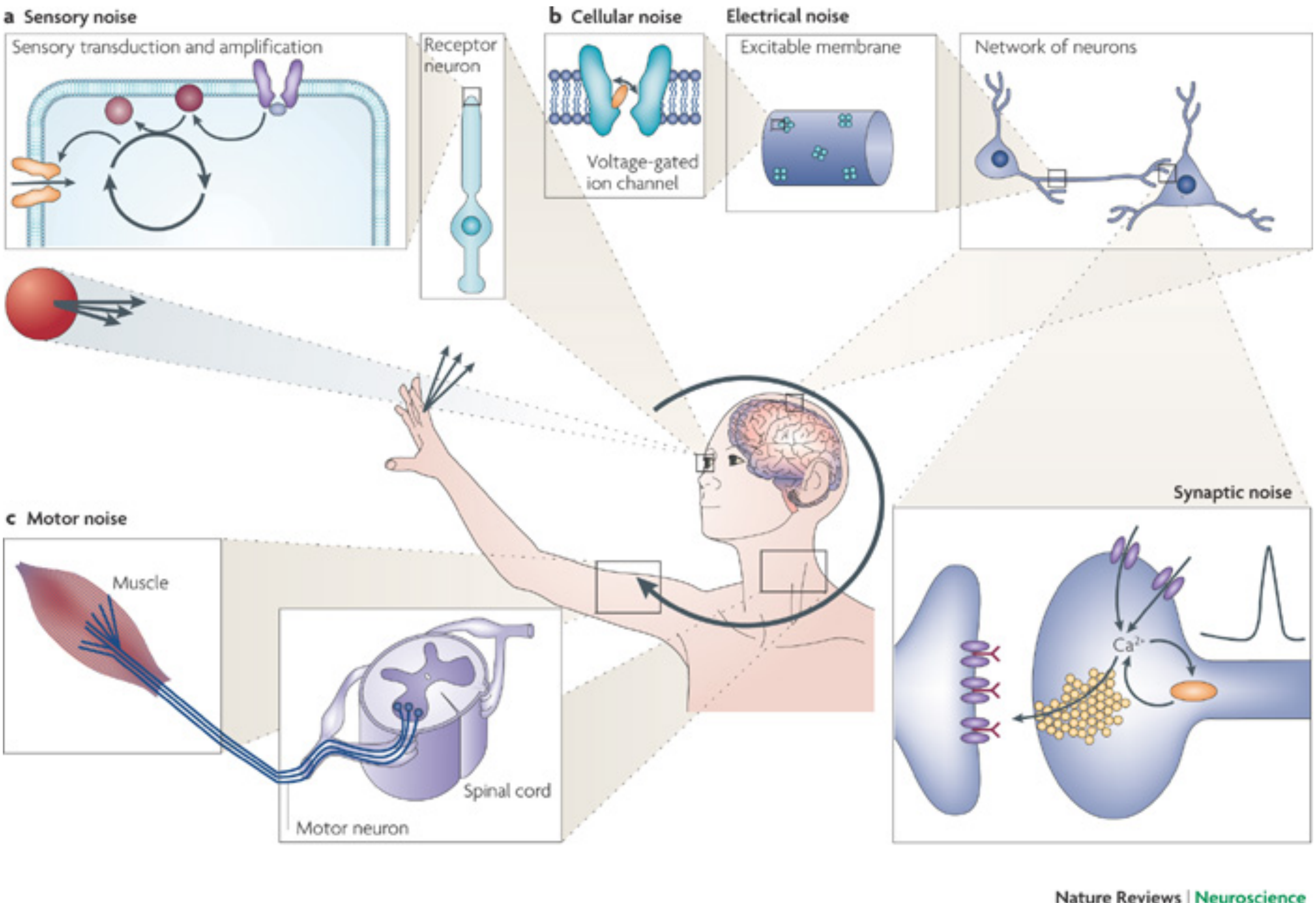


Thus, organisms pay a high metabolic and structural price at the first stage of processing (the sensory stage).

- A fly's photoreceptors account for 10% of its resting metabolic consumption and its eye's optics make up over 20% of the flight payload.



Noise in the Nervous System



Cellular Noise

Stochastic process (random process): A process that generates a series of random events.

Positive feedback: feedback that responds to a perturbation in the same direction as the perturbation, thereby amplifying its effect.

If neurons are driven with identical time-varying stimuli over trials, the timing of resultant action potentials varies over time.

Is this meaningful processing or noise?

Neuronal activity may appear random without actually being random.

What are the sources of noise in neurons?

- Randomness in cellular machinery that processes information
- Non-linear computations and network interactions at population level

Electrical Noise and Action Potentials

Nodes of Ranvier: Regularly spaced gaps in the myelin sheath that surrounds a myelinated axon. They expose the axonal membrane to the extracellular fluid and contain large numbers of voltage-gated ion channels and thus enable conduction of the action potential.

Patch-clamp technique: An electrophysiological method that allows the study of the flow of current through a very small patch of cell membrane, which can contain just a single ion channel.

At population level, neurons perform highly non-linear operations that involve high-gain amplification and positive feedback.

At biochemical level, stochastic processes at work in neurons include:

- Protein production and degradation
- Opening and closing of ion channels
- Fusing of synaptic vesicles
- Diffusion and binding of signaling molecules to receptors

Action Potential Propagation

Channel noise:

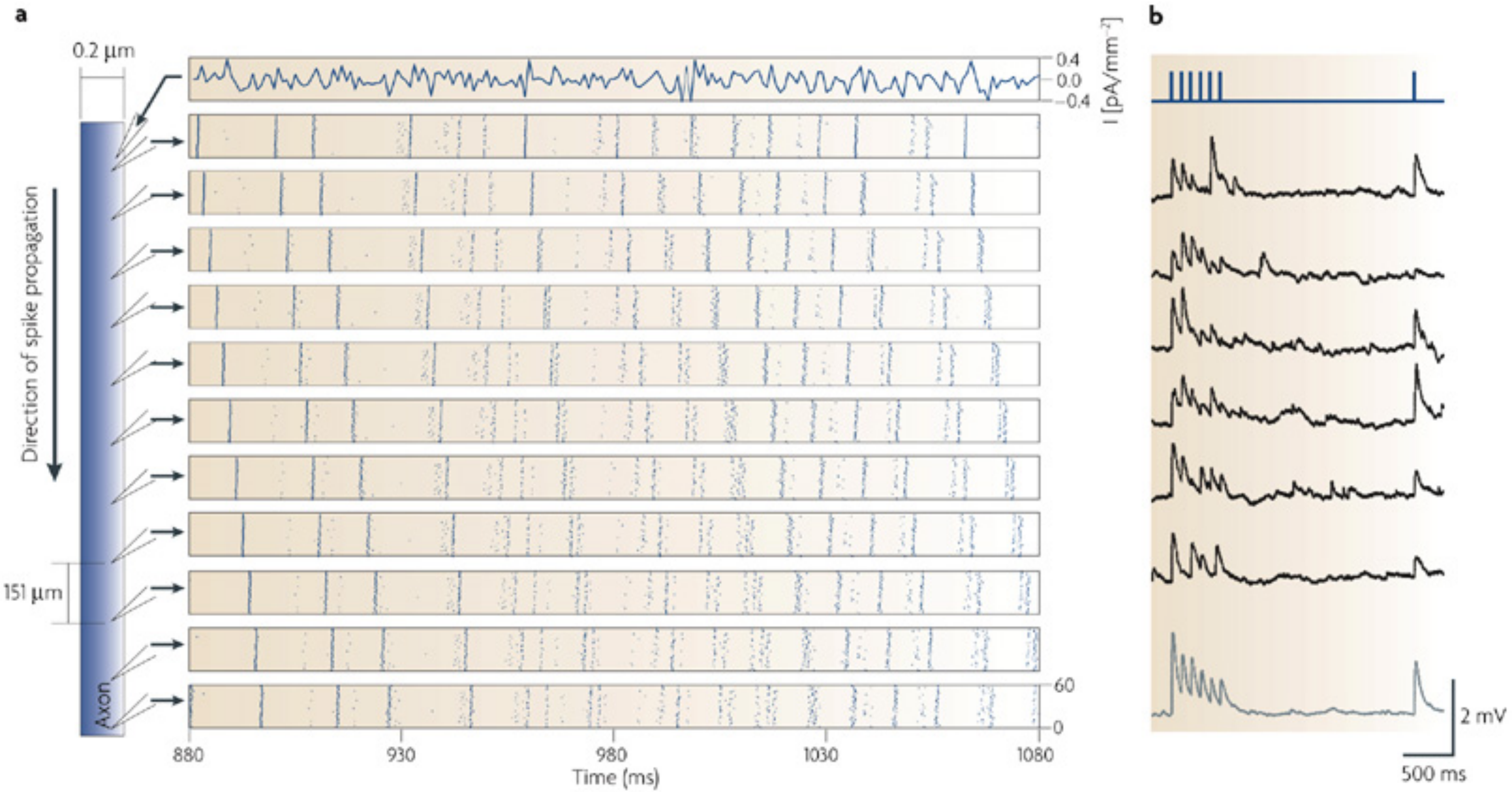
electrical currents produced by random opening and closing of voltage-gated or ligand-gated ion channels

- Computational models have shown that channel noise can account for variability in action potential threshold at nodes of Ranvier
- Patch-clamp experiments done in vitro have shown that channel noise in dendrites and in soma produce membrane potential fluctuations that are large enough to act action potential timing

The site of action potential is at the axon hillock. As cells vary in size (radii influences speed of conduction), this shapes the number of ion channels present for action potential firing.

In this way, thermodynamic noise in individual ion channel proteins sets an upper limit to the wiring densities of the brain.

Cortical Variability



a. Channel noise as a source of trial-to-trial variability in action potential propagation
b. Trial-to-trial variability of synaptic transmission measured by *in vitro* patch-clamp recordings

Action Potential Propagation

Johnson noise: The electric noise that is generated by the thermal agitation of the charge carriers (electrons and ions) inside an electrical conductor at equilibrium, which happens regardless of any applied voltage.

Shot noise: A type of noise that occurs when the finite number of signal particles, such as electrons or ions in an electrical circuit or photons arriving at a photoreceptor, is small enough to give rise to detectable statistical fluctuations in a measurement.

Ephaptic coupling: The coupling of very close or touching neurons, mediated by the electrical fields the neurons generate during electrical activity.

What influences action potential propagation?

- Johnson noise and Shot noise
- Ionic current flowing inside axon influences speed
- Cross-talk among neurons by ephaptic coupling
- Spill-over of neurotransmitters between unrelated synapses

Noise produces nonlinearity

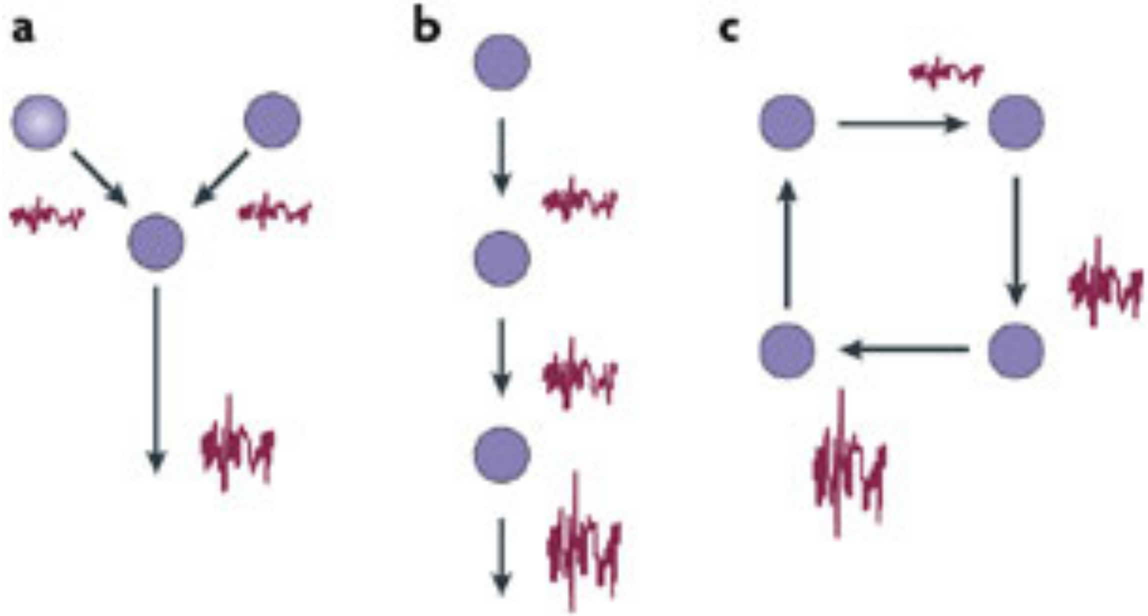
In spike-generating neurons, sub-threshold signals have no effect on the output of the system. Noise can transform such threshold nonlinearities by making sub-threshold inputs more likely to cross the threshold, and this becomes more likely the closer the inputs are to the threshold.

> *Thus, when outputs are averaged over time, this noise produces an effectively smoothed nonlinearity.*

This facilitates spike initiation and can improve neural network behavior, as was shown in studies of contrast invariance of orientation tuning in the primary visual cortex.

Neuronal networks in the presence of noise will be more robust and explore more states, facilitating learning and adaptation to the changing demands of a dynamic environment.

Noise build-up in networks



How can neural networks maintain stable activity in the presence of noise?

a. Converge of signals onto a single neuron.
b. Passage of signals through a series of neurons.
c. Recurrence in networks results in build-up of correlated noise.

How does the brain manage noise?

Homeostatic plasticity mechanisms

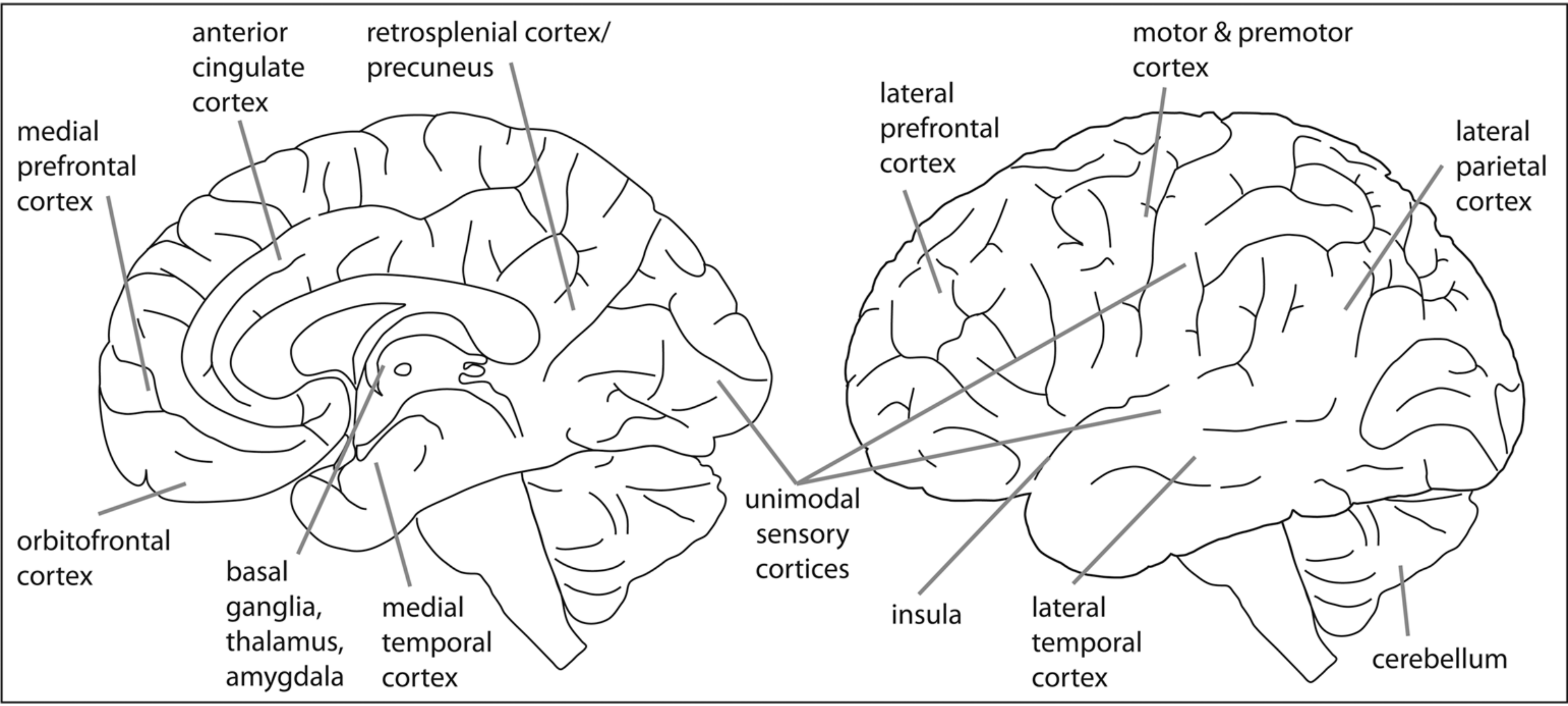
- Neuronal activity levels are maintained by homeostatic plasticity mechanisms that dynamically set synaptic strengths, ion channel expression and the release of neuromodulators.
- This suggests that networks of neurons can dynamically adjust to attenuate noise effects. Moreover, these networks might be wired so that large variations in the response properties of single neurons have little effect on network behavior.

The principle of averaging can be applied whenever redundant information is present across the sensory inputs to the central nervous system.

Divergence (one neuron synapsing onto many) can also support averaging.

When signals are sent over long distances through noisy axons, rather than using a single axon, it can be beneficial to send the same signal redundantly over multiple axons and then combine these signals at the destination.

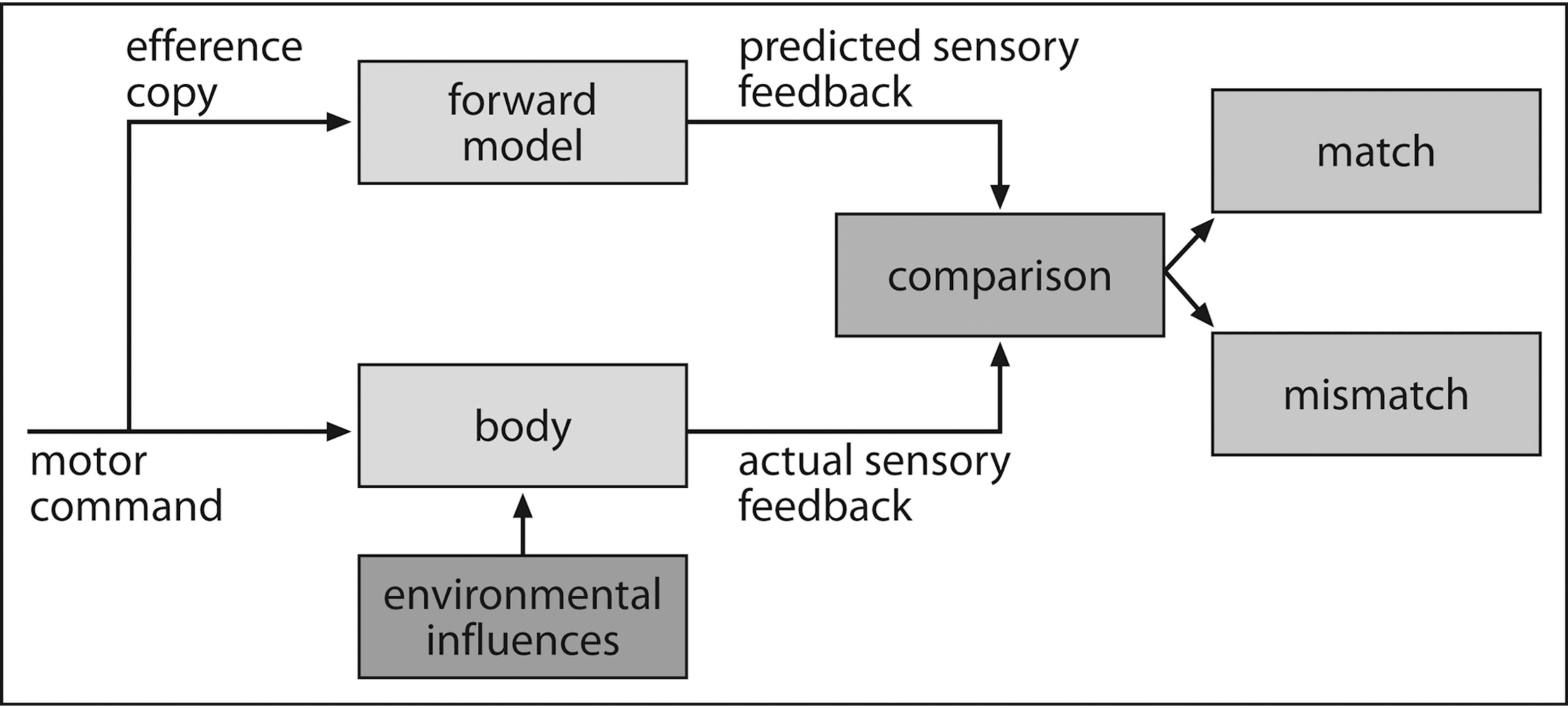
The Predictive Brain



How does the visual world remain stable despite constant head and eye movements?

The predictive brain— in this case, motor activation influences sensory processing. There is information on the past, present, and future.

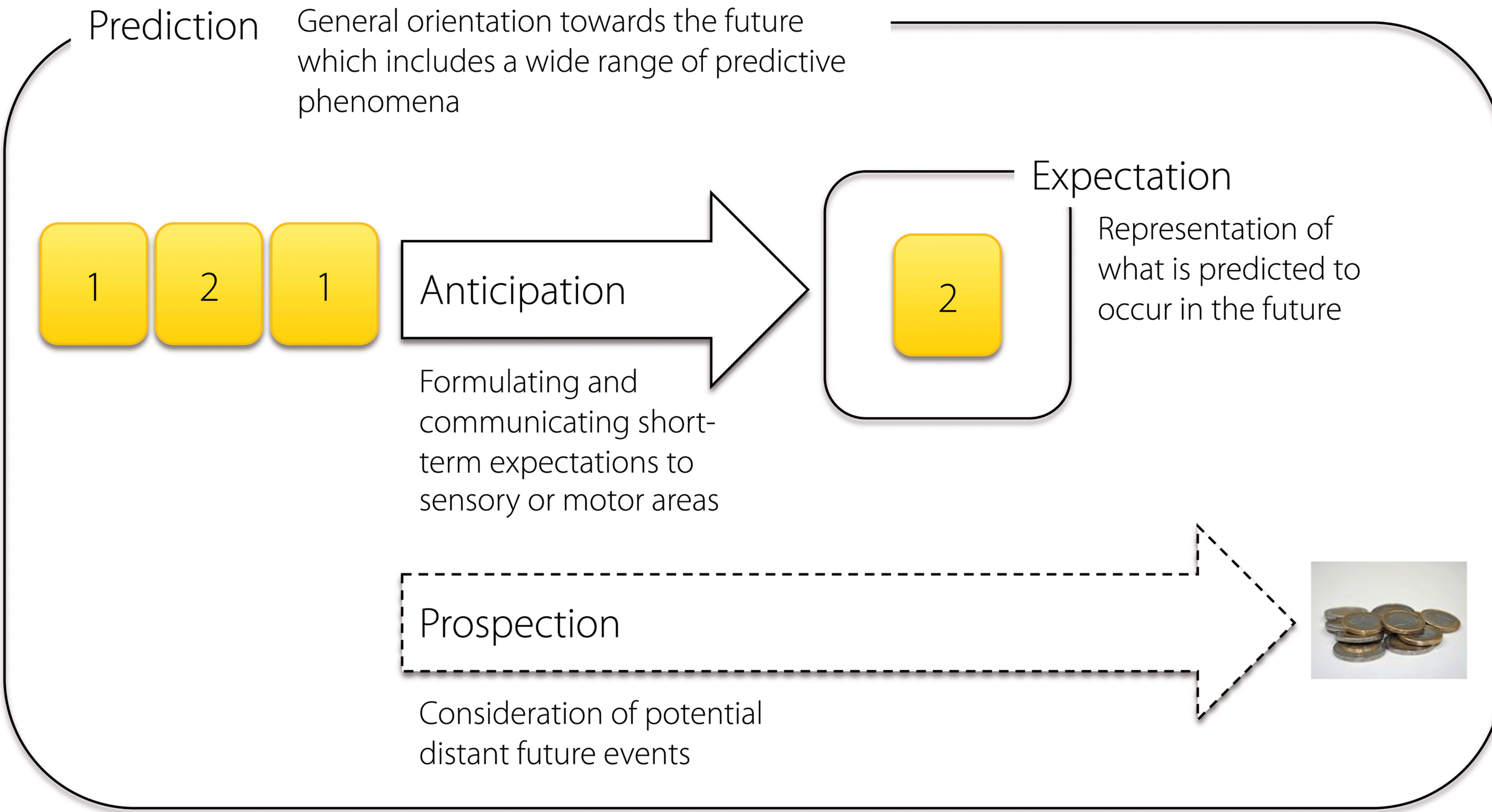
Prediction in Motor Control

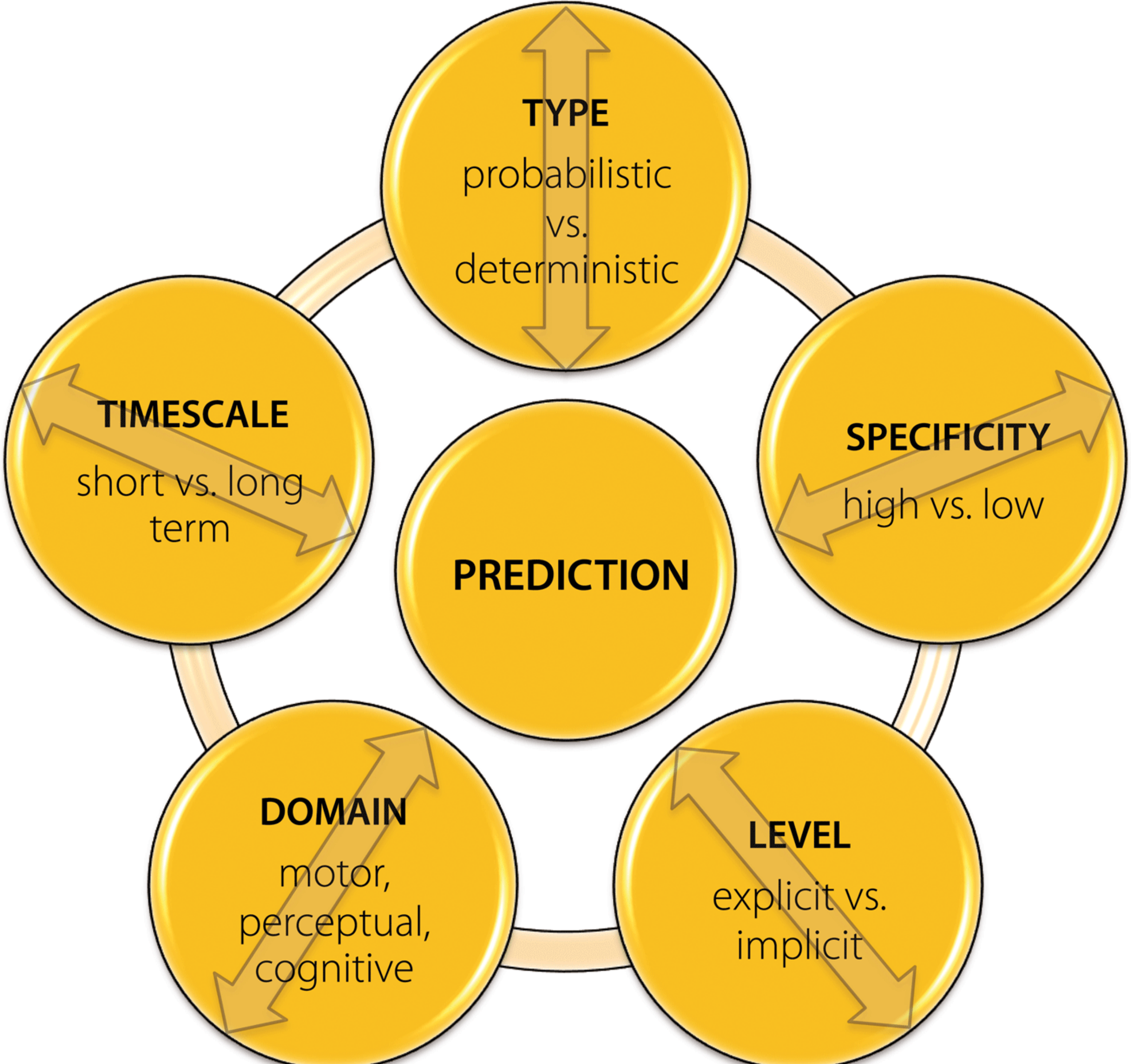


Efference copy: internal copy of outflowing information (efferent), movement-producing signal generation by motor system

i.e. Other people can tickle us (no efference copy) but we cannot tickle ourselves.

Prediction Model




TYPE
probabilistic
vs.
deterministic
SPECIFICITY
high vs. low
LEVEL
explicit vs.
implicit
DOMAIN
motor,
perceptual,
cognitive
TIMESCALE
short vs. long
term
PREDICTION

Prediction in the Brain

Pre-Requisites:

Events are non-random

We can then use learning and identify associations. In this way, we can accumulate information related to statistical regularities while dealing with noise and uncertainty in the environment.

Benefits:

- Expectations allow us to construct a coherent and stable representation of our noisy and delayed environment
- Prediction allows us to act

***Ideo-motor principle**:* anticipated sensory consequences of one's actions can trigger and guide behavior

Why is this important?

We are constantly oriented towards the future— we formulate our intentions and plan our future actions. This is our planning or prospective memory.

When Predictions Meet Reality

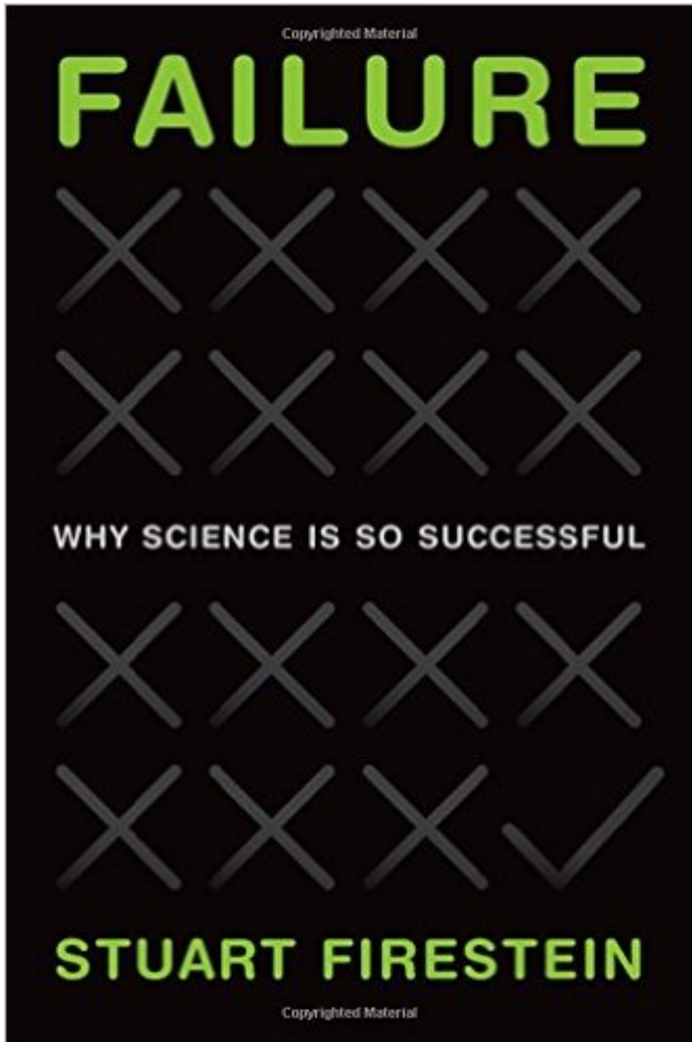
Efficiency is not equal to relevance or associated priority.

Why?

Unsuccessful matches are critical to learning. We arguably learn the most when we fail.

In this way, errors of prediction have greater value and may signal unsuccessful learning, a major change in surrounding, or noise.

Novel or unexpected events are preferentially detected and encoded. This may explain why a *discrepancy* between expected and realized events is a driving force for learning. At the neuronal level, this discrepancy is represented by *a change in synaptic weights*.



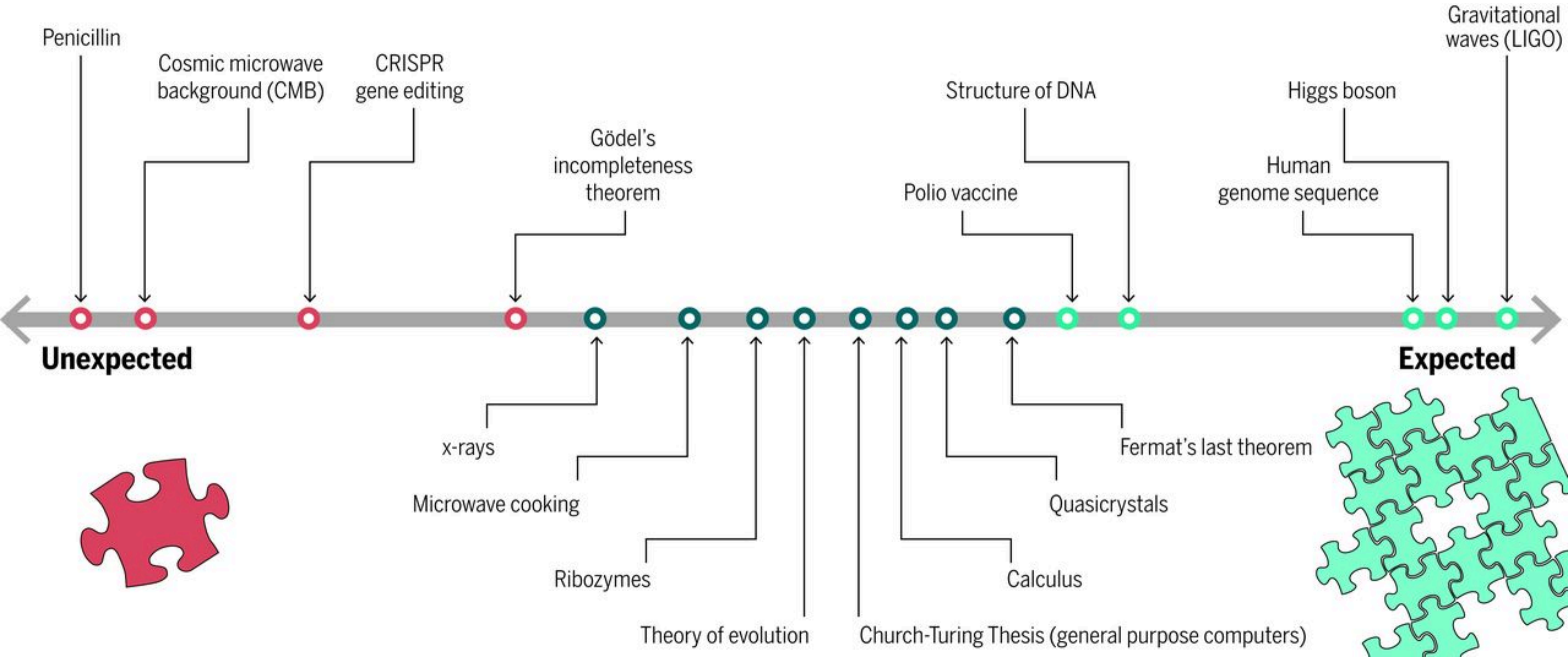
Predictive Models

We currently can (and cannot) predict using the emerging conjunction of machine learning, big data, and human understanding.

How unexpected is a discovery?

The desire to predict discoveries pervades modern science:

- Scientists predict what research topics are interesting, impactful, and fundable.
- Publishers and funding agencies evaluate projects by predicting their future impact.
- *The more predictable we can make the process of scientific discovery, the more efficiently those resources can be used.*



Psychological Review
Vol. 65, No. 6, 1958

THE PERCEPTRON: A PROBABILISTIC MODEL FOR INFORMATION STORAGE AND ORGANIZATION IN THE BRAIN[1]

F. ROSENBLATT

Cornell Aeronautical Laboratory

Some discoveries do not follow the rules, and the exceptions demonstrate that there can be more to scientific impact than visibility, luck, and positive feedback.

“Sleeping beauties” in science: discoveries that lay dormant and largely unnoticed for long periods of time before suddenly attracting great attention

- *1958 paper by Rosenblatt on artificial neural networks*

Next Time:

Stories from Japan

Osaka
Kyoto
Tokyo